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Reference:
Berkvens Rafael, Bellekens Ben, Weyn Maarten.- Signal strength indoor localization using a single DASH7 message
Proceedings of the 8th International Conference on Indoor Positioning and Indoor Navigation, (IPIN), SEP 18-21, 2017, Sapporo, JAPAN - ISSN 2162-7347 - New York, IEEE, (2017)7 p.
Full text (Publisher's DOI): https://doi.org/10.1109/IPIN.2017.8115875
To cite this reference: http://hdl.handle.net/10067/1486260151162165141

Signal Strength Indoor Localization using a Single DASH7 Message

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***Abstract*—In the Internet of Things, location information is crucial for many applications. We want to obtain location information from a device by using its existing communication modality. DASH7 is designed for low power sensor and actuator communication on a medium range, using the license exempt radio frequency channels below one gigahertz. In this paper, we present a method to localize a DASH7 mobile node based on a single message and a deterministic propagation model. The propagation model is used to indicate the distance between sender and receiver so that single measurement localization approach is possible without maintaining a fingerprint database. We obtain a median location error of 3.9 m, where we still see room for improvement.**

***Keywords*—DASH7, signal strength ranging, multi-wall model, 433 MHz**

I. Introduction

Automated inventory management is one of the top three use cases driving the Internet of Things [1]. However, locating where inventory items are stored remains a challenge in all but the most automated environments. Since human interaction and forgetfulness will remain in most environments that cannot be fully robotized—such as warehouses with limited financial budgets, hospitals, or construction sites—it is useful to create a wireless positioning system to facilitate the retrieval of inventory items.

Several technologies for wireless positioning systems have already been proposed. Wi-Fi fingerprinting is a well established positioning technique with fair accuracy [2]. The downside of Wi-Fi fingerprinting is that the training phase is usually labor intensive and may have to be repeated whenever the environment changes. Bluetooth Low Energy (BLE) beacons are used to improve Wi-Fi positioning [3], or as standalone positioning systems [4]. BLE localization benefits from the fact that many beacons can be installed, but this high number usually requires them to run on batteries which need frequent replacement. Ultra-Wide Band (UWB) localization can be very accurate even in challenging environments [5], yet requires line of sight for optimal performance, which cannot always be guaranteed in unstructured environments. While this list is not comprehensive, it does show that many wireless communication technologies can be used for localization, albeit each with its own considerations.

DASH7 is a wireless communication protocol that aims for medium range, low power communication [6]. It is based on the Radio Frequency Identification (RFID) ISO 18000-7 standard. DASH7, however, is capable of more than just RFID—it is a complete sensor and actuator communication protocol, implementing each layer of the OSI model. For its physical layer, DASH7 uses the Industrial, Scientific, and Medial (ISM) communication frequency at 433 MHz and the license exempt Short Range Devices (SRD) communication at 868 MHz in Europe. It has three data rates, with the lowest rate specifically intended for very long range communication. This has lead our research group to investigate the use of DASH7 for Internet of Things applications, such as automated inventory management. Contextual information, especially the location of a device, is crucial in such systems. Therefore, in this study, we investigated how accurately we can localize DASH7 devices.

Localization using DASH7 has been studied before [7], [8], but not for single step localization, *i.e.* calculating the location given a single measurement and no history. In this paper, we will present results of single step DASH7 localization based on a multi-wall propagation model and signal strength ranging from a single message. Tuset-Pieró *et al.* [9] discussed the suitability of 433 MHz and 2.45 GHz in both indoor and outdoor environments. As he discussed and illustrated the aspects of small-scale fading on top of large-scale fading in indoor environments, the results show a high potential when using 433 MHz for M2M applications. We want to use only a single message to minimize the energy cost for the mobile unit. The different ranging hypotheses will be combined by probabilistic fusion. We use a 1122 m^2 office environment to test the localization performance.

This paper begins, in Section II, by describing how we performed our measurements. Subsequently, we outline the propagation model in Section III and the localization method in Section IV. Next, we discuss our results in Section V and draw conclusions in Section VI.

II. Measurements Methodology

In order to analyze the location error, measurements were collected using the DASH7 Alliance protocol. A DASH7 network is typically applied as a star topology, although one-hop routing is an optional functionality which is not applied in our situation. The star topology DASH7 network consists of one or more gateways and endpoints. The gateways are applied in the center of the star topology in such a way that

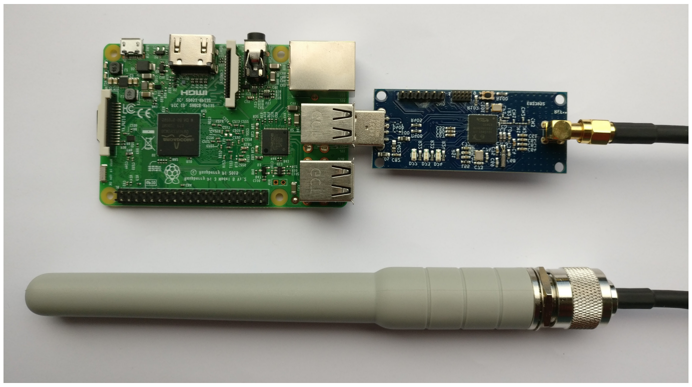

Fig. 1. DASH7 gateway setup that exists of a raspberry pi, a DASH7 USB dongle and a monopole antenna

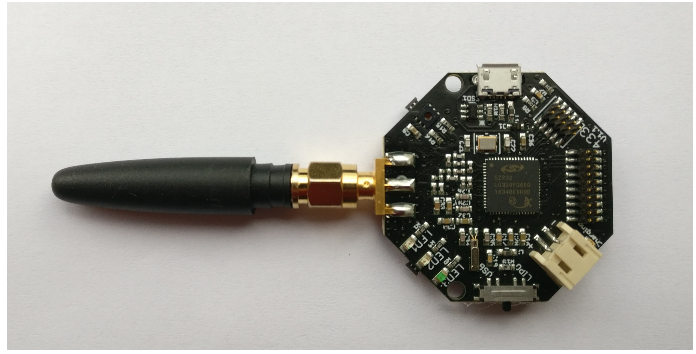

Fig. 2. DASH7 Octa-mini that is equipped with an external monopole antenna.

it receives messages from mobile endpoints. An asynchronous communication scheme is typically applied in DASH7 networks, and two-way communication is possible between both transmitter and receiver. This enables two types of applications which differ in their power profile. First, the mobile sensor can broadcast messages based on a time schedule or it can be triggered with an action such as pressing a button. Secondly, assuming that the operating space of the mobile nodes has full wireless connectivity, the gateways are able to poll for specific measurements based on a triggered action such as an emergency alarm. Based on both situations the power profile of the mobile node will be different. This can be explained by the fact that periodically sending data consumes more power than ad-hoc polling, which is also application dependent. So, for example sending the temperature of a room every minute can consume more power than requesting the temperature when necessary.

In our setup, we scattered six DASH7 gateways throughout the environment. The DASH7 gateway exists of different parts as can be seen Figure 1. First, an embedded device is used to read the received DASH7-messages from a serial connection. Additionally, this device will forward the messages to the cloud where it will be stored for further analysis. Secondly, a DASH7 USB-dongle is used to receive a message on the 433 MHz ISM band. This USB-dongle is equipped with a Silicon Labs EZR32LG330F256 radio-chip and is programmed to receive a DASH7-message using the open-source library[1]. Finally, an external monopole antenna that is matched on 433 MHz, with a gain of 3 dBi is used for reception. While we did not optimize the gateway locations towards an optimal localization performance, we did aim to make sure they were evenly distributed.

Subsequently, we placed a DASH7 Octa-mini on 25 different locations in the environment. Figure 3 shows the locations of both the gateways with red dots and the mobile nodes with green triangles. Every Octa-mini, as shown in Figure 2, is programmed to broadcast a DASH7-message twice per second on the 433 MHz ISM band with a transmit power of 10 dBm using the DASH7 open-source library[1]. For this scenario we used the first type of communication where the mobile node periodically sends information to the gateway, as explained above. Although DASH7 makes it possible to enable Quality of Service (QoS) which will send an acknowledgement after a message is acquired, this feature is disabled in our scenario. We will only use one message, one received signal strength measurement, causing channel overhead and power profile will to be lower. Additionally, an external monopole antenna of 3 dBi is applied on the mobile nodes.

In the localization procedure, we will use only one message to calculate the location, because we are interested in determining the position of a device that might send or requested a message only once per hour or per day. Doing so will require only little energy: the message has an energy cost of 0.379 mJ, based on a transmission current of 27 mA, a working voltage of 3.3 V, and a transmission time of 4.3 ms. This message energy cost can be compared with 1187 J in 2.4 GHz and 9.7 J in 915 MHz using the IEEE 802.15.4 physical layer [10]. However, increasing the transmission rate for our experiment allowed us to quickly gather more data. Simultaneously, the gateways listened for DASH7 messages on the same 433 MHz ISM band and reported the signal strength with which they received these messages to the server. These signal strengths are then used to calculate the most likely distance between the receiving gateway and the transmitting endpoint node, based on following multi-wall propagation model.

III. Propagation model

When wireless devices are connected, the received signal strength will be measured at the receiver side. The received signal strength can generally be modeled using a propagation loss model, which simulates the transmission loss between two radiating antennas. Two main types of propagation models can be distinguished: (i) empirical and (ii) deterministic models. They differ in their complexity, precision and accuracy. On one hand, empirical loss models are least accurate, but also the least complex, as they provide a statistical solution based on multiple measurements. These models do not include the small scale fading effects, which results in good accuracy and low precision compared to the deterministic models. On the

[1]https://github.com/MOSAIC-LoPoW/dash7-ap-open-source-stack

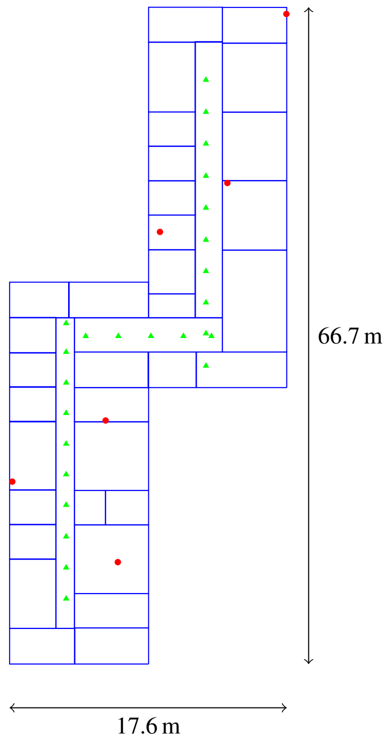

Fig. 3. Experiment's environment and test setup. The red dots are the gateways' locations. The green triangles are the test locations.

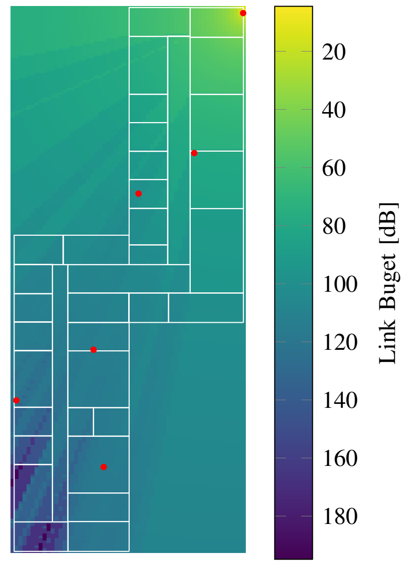

Fig. 4. The link budget values of the gateway in the north east corner of the environment are simulated based on the multi-wall propagation model.

other hand, deterministic models are more accurate and more precise. Furthermore, deterministic models can be subdivided in two different types: site-general and site-specific models. Because of the introduction of site-specific simulations where reflection, refraction, and diffraction are included on top of the large scale fading effect, very detailed knowledge can be obtained from the radio propagation. This does require a high computational complexity. However, the environment should be modeled with much more details, such as the roughness of the walls, inclusion of objects, ceilings, floors, furniture, and material properties. Site-general models are a good trade-off in order to obtain a reasonable result with little path and limited environment knowledge with the advantage of a low computational complexity.

Within this research, a multi-wall model is applied to simulate the reception of a mobile device in an indoor environment [11]. This model can be categorized as a site-general model which includes: the free space propagation loss due to the physical medium and the attenuation loss due to the walls and floors. Such a simulation will, in the first place, model a description of the environment that holds the dimensions of the environment and the locations of the transmitters and the receivers. Secondly, the simulation models the environment based on an equally sized grid with a resolution of 0.3 m.

This grid-based environment will enable it to compute the euclidean distance between each grid cell and the transmitter. Based on this distance, the link budget L can be computed according to the extended ITU model that has following equation [11], [12]:

$$L = 20\log_{10} f + 10n\log_{10} d + X_\alpha(k) + L_f(m) - 28, \quad (1)$$

where d is the euclidean distance between both devices, f is the operating frequency expressed in megahertz, $L_f(m)$ is the attenuation loss as a result of the floor penetrations. This floor attenuation loss will be zero in our use case because of all measurements were applied at the same floor. Next, the number of wall penetration is computed by calculating the amount of intersections between each grid cell and the selected transmitter location. This number of wall penetrations k will be used as input to determine the attenuation path loss X_α according to the given formula that is being fitted for 900 MHz [11]:

$$X_\alpha(k) = 0.0075k^4 - 0.18k^3 + 1.11k^2 + 2.9k. \quad (2)$$

Figure 4 shows the result of applying this link budget analysis for each grid cell of the environment. It indicates the signal strength relative to transmitter in the north east corner.

IV. Localization method

We want to determine the location of a DASH7 node that transmitted a single message. Several DASH7 gateways, preferably three or more, receive this message. The gateways determine the link budget and report this to a central server. These link budgets are then translated to a likely range between the node and the gateway. Finally, the combination of the different ranges indicates the location estimate.

Since we utilize a multi-wall propagation model, the distance between the node and gateway is not a simple circle, but is smaller when more walls obstruct the line of sight path. The propagation model is calculated on a grid with a cell width of 0.3 m. This allows us to establish a likelihood of the link budget reported by the gateway at each location in the

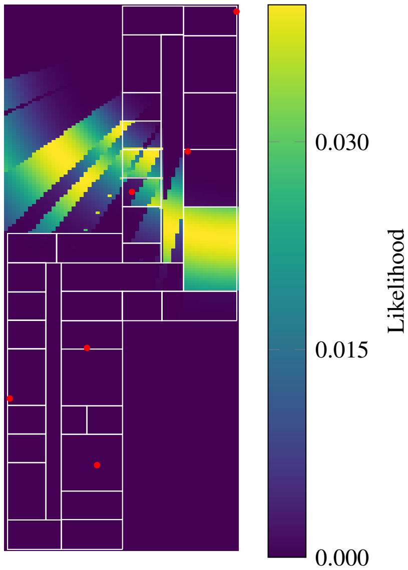

Fig. 5. Location likelihood of a mobile node that has a link budget of 93 dB.

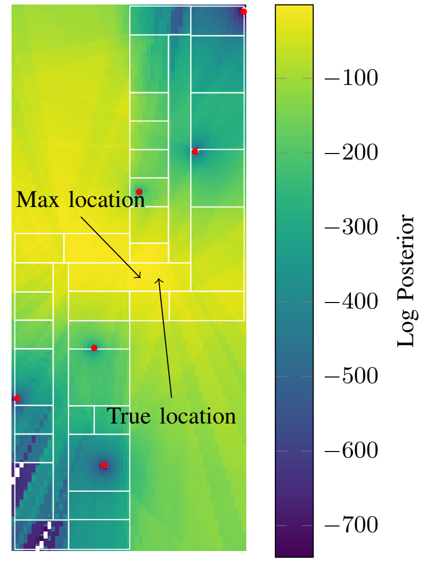

Fig. 6. The posterior distribution is calculated from the likelihoods of the range estimations to the different gateways. The location with the maximum posterior value becomes the location estimate. Note that the log posterior is shown for additional clarity.

environment. The measured link budget between the mobile node and gateway n is L_n^m. The likelihood at each location X is $p(L_n \mid X)$, calculated by a comparing the measured link budget with the link budget from the multi-wall model L_n through a normal distribution:

$$p(L_n \mid X) = \frac{1}{\sqrt{2\pi}\sigma} \exp - \frac{(L_n^m - L_n)^2}{2\sigma^2}, \tag{3}$$

where σ is determined experimentally based on 826 measurements from two gateways, resulting in 2.74 dB. When applied to the same gateway as in Figure 4, this results in the likelihood distribution shown in Figure 5 when the measured link budget is 93 dB.

The likelihoods from all the different gateways N in a single link budget measurement L are multiplied to create the joint likelihood distribution:

$$p(L \mid X) = \prod_{n}^{N} p(L_n \mid X). \tag{4}$$

Subsequently, the joint likelihood becomes the posterior distribution over the locations by following Bayes' rule:

$$p(X \mid L) = \frac{p(L \mid X)p(X)}{\sum_X p(L \mid X)}, \tag{5}$$

where we use a uniform prior $p(X)$, since we do not presume to have any prior knowledge of where the mobile node is located. Figure 6 shows an example posterior calculated by Equation (5).

Finally, we choose the location with the highest posterior probability as the location of the mobile node, known as the Maximum A Posteriori (MAP) approach. There is a possibility that there are multiple locations with equal posterior probability, especially in the rare case of only one or two gateways that receive the message. In this case, the first location in the grid with such posterior is selected. Optimization of this step is possible, yet at this point we did not want to influence the results with optimizations.

The location error is defined as the Euclidean distance between the MAP location and the true location of the mobile node.

V. Results

This section analyses the performance of both the localization method and the propagation model. To illustrate the performance of the propagation model, we analyzed the received link budget according to the simulated values at the receiver locations. Furthermore the localization performance is illustrated using the cumulative distribution function of the location error for all messages and is further discussed in the subsection below.

A. localization Analysis

On average, four gateways receive the message from the mobile node. Less than 5.2 % of the messages are received by fewer than three gateways. 19.6 % of the messages are received by all six gateways.

Figure 7 shows the cumulative distribution of the location error for all messages. As summarized in Table I, the mean location error is 5.3 m, with a standard deviation of 4.1 m. The median location error is 3.9 m. This indicates that half of the messages from the mobile node could be located within 3.9 m, which could be sufficient in some scenarios, but which is still a rather large error. The 75th percentile location error is 6.6 m, close to the root mean square location error of 6.7 m.

The large discrepancy between the mean and median location error, and the rather high 75th percentile location error is most likely caused by a number of outliers. This effect can

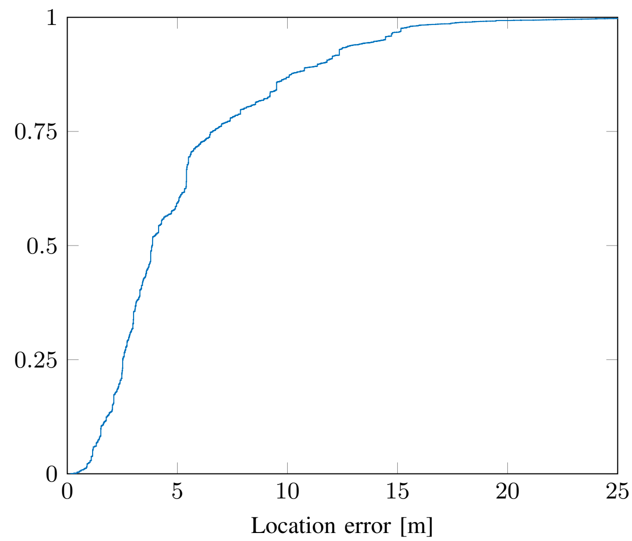

Fig. 7. Cumulative distribution of the location error for each message send at all the 25 test locations.

TABLE I
SUMMARY OF THE LOCATION ERROR RESULTS.

Mean	5.3 m
Median	3.9 m
Standard deviation	4.1 m
75th percentile	6.6 m
Root mean squared	6.7 m

be reduced by increasing the number of messages used for localization. While our setup is aimed at using just a single message, in order to reduce the power consumption, we can calculate the location error when the average location estimate would be used for a number of messages. With three messages, the mean location error would reduce to 4.9 m, and the 75th percentile to 5.7 m. With five messages, the mean location error reduces to 4.8 m, and the 75th percentile remains 5.7 m. Thus, increasing the number of messages does not decrease the location error dramatically.

B. Propagation Model Validation

To illustrate the performance of our multi-wall propagation model, a validation of the received link budget is performed by comparing to the simulated values at locations where a measurement was performed, as in [13]. Figure 8 and 9 show the differences between the measured and the simulated values for the gateways that are located in the upper right and lower right corner of Figure 3.

As can be noticed in Figure 8, none of the transmitted messages from the first ten locations are received by this gateway. Because of the sensitivity level of a DASH7 USB-node, which is −115 dBm, the device does not detect any signals at these locations. Furthermore, when the distance between sender and receiver and the number of wall intersections are small, a large offset is computed between the simulated and the measured values. This is the result of using the site-

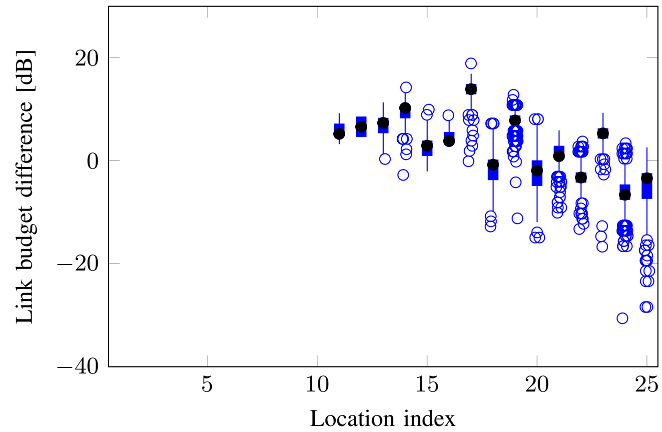

Fig. 8. Error in the link budget of the gateway in the upper right corner.

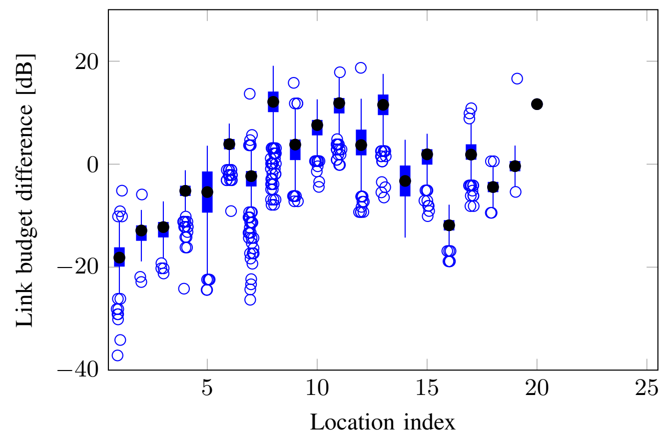

Fig. 9. Error in the link budget of the gateway in the lower right corner.

generic propagation model. As discussed in Section III, the propagation model first calculates the propagation loss and secondly it will calculate an additional attenuation loss when the signal penetrates throughout walls. This function, as shown in Figure 10, will have a low attenuation loss when a few walls are penetrated.

According to this function and our sensitivity level, it is impossible to receive any messages when more then 18 intersections occurs. So when a few intersections occur, the offset will be large because of the fact that several factors like reflections, diffractions and the effect of constructive and destructive wave propagation are neglected. Besides, when the distance and the number of intersections are large, the offset is much smaller. This result can be analyzed from Figure 11, which shows the results of a gateway that is located in the middle of the environment. The first five and the last five locations will have a reasonable offset, while the others have a large difference due to the reflections, diffractions and the effect of constructive and destructive wave propagation. This lack of propagation accuracy can lead to a localization likelihood that is insufficient for a localization system with small location error.

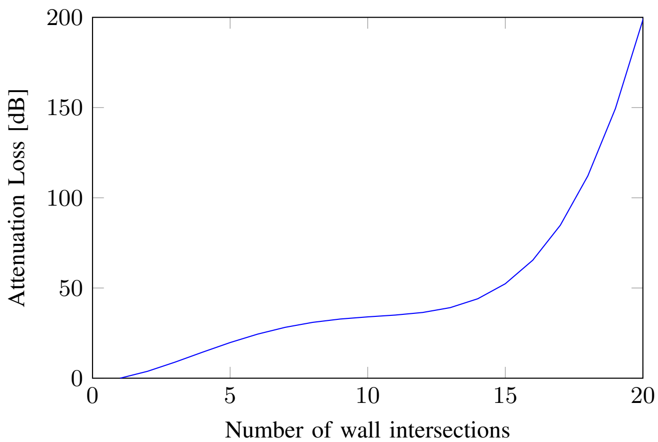

Fig. 10. The added attenuation loss in function of the number of wall intersections according to equation (2).

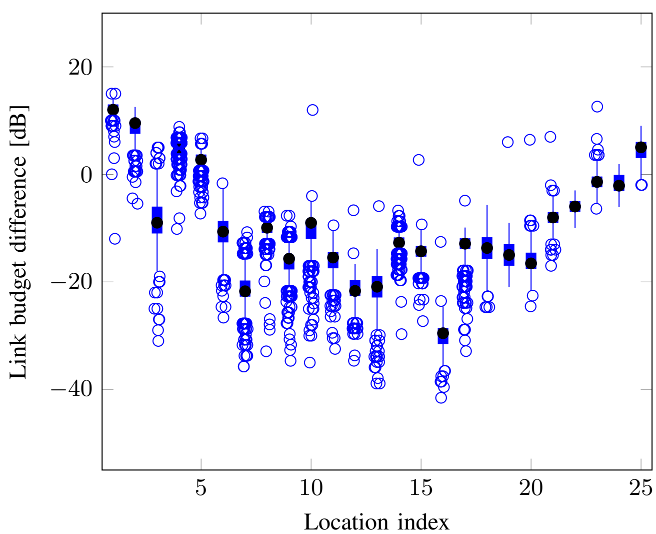

Fig. 11. Error in the link budget of the gateway in the middle of the environment.

VI. Conclusion

This paper presents the results of localizing a mobile DASH7 node based on a single message received by multiple gateways. The distances between the node and the gateways are estimated based on a multi-wall propagation model. Furthermore, the radio signal is situated on the 433 MHz ISM band. The median location error of this approach is 3.9 m. This location error is rather small compared to the large offset that we obtain when validating the propagation model.

Since this DASH7 localization system is based on received signal strength ranging through a multi-wall propagation model, there is no requirement to maintain a fingerprinting database, while it still obtains a location error comparable to that of state-of-the-art Wi-Fi fingerprinting localization systems [2]. Moreover, DASH7 is designed as a low power communication system, thus transmitting the single message that is required for those results should be very power efficient.

While this work is very valuable as the first benchmark of DASH7 location estimation based on a single message, some improvements can still be made. The multi-wall model is based on the model from Ata *et al.* [11], which is intended for 900 MHz. The parameters in Equation (2) should be calibrated specifically for the DASH7 frequencies (433 Hz and 868 Hz in Europe). Furthermore, the multi-wall model is a site-general deterministic propagation model, so it does not take into account details specific to the environment, only the location of the walls. We are currently developing a site-specific deterministic propagation model, which should allow us to further decrease the location error due to a lower offset between the measured and the simulated signal strength.

Acknowledgment

Part of this work was funded by the MuSCLe-IoT (Multimodal Sub-Gigahertz Communication and Localization for Low-power IoT applications) project, co-funded by imec, a research institute founded by the Flemish Government, with project support from VLAIO (contract number HBC.2016.0660). Part of this research was funded by the Flemish FWO SBO S004017N IDEAL-IoT (Intelligent DEnse And Longe range IoT networks) project.

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